Digital Low-Pass Filter Implementation #1

Define sampling frequency

$Fs := 44100$

Define cutoff frequency

$Fc := 14000$

Normalized cutoff frequency

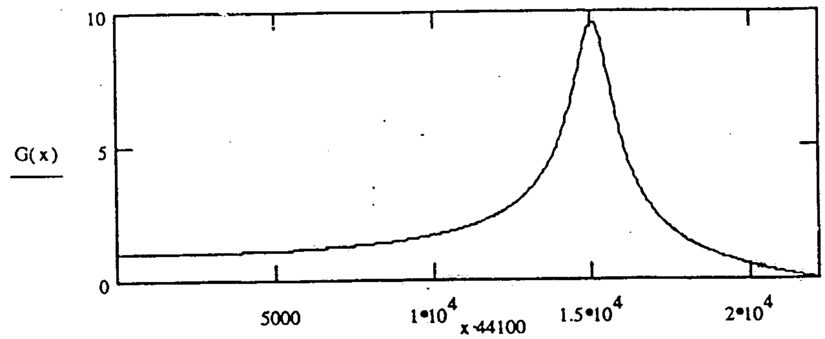
$fc := 2 \cdot \frac{Fc}{Fs}$

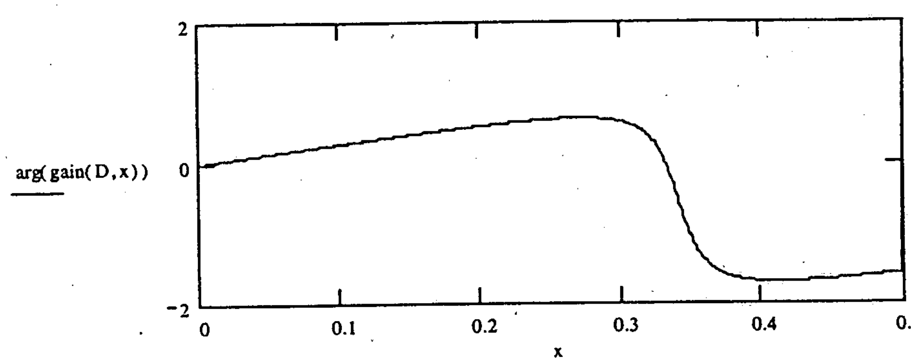
$fc = 0.635$

Define Filter Q

$q := 10$

$Q := \frac{1}{q}$





Define Filter Parameters

$F := 2 \cdot \sin\left(fc \cdot \frac{\pi}{2}\right)$

$F = 1.68$

$A := \frac{F^2}{2}$

$A = 1.411$

$B := A$

Define Transfer Function (1st column is numerator coefficients in transfer function and 2nd column is denominator coefficients in transfer function). So this filter is a 2nd order IIR.

$$D := \begin{bmatrix} B & 1 \\ B & -\left(2 - F \cdot Q - F^2\right) \\ 0 & (1 - F \cdot Q) \end{bmatrix}$$

$$D = \begin{bmatrix} 1.411 & 1 \\ 1.411 & 0.991 \\ 0 & 0.832 \end{bmatrix}$$

Plot frequency and phase response of the filter

$x := 0, .001 .. .5$

$G(x) := \left| gain(D, x) \right|$

FIG. A1

Digital Hi-Pass Filter #1

Define sampling frequency

$Fs := 44100$

Define cutoff frequency

$Fc := 2000$

Normalized cutoff frequency

$fc := 2 \cdot \frac{Fc}{Fs}$

Define Filter Q

$q := 2$

$Q := \frac{1}{q}$

Define Filter Parameters

$F := 2 \cdot \sin\left(fc \cdot \frac{\pi}{2}\right)$

$F = 0.284$

$A := \frac{F^2}{2}$

$A = 0.04$

$B := A$

Define Transfer Function (1st column is numerator coefficients in transfer function and 2nd column is denominator coefficients in transfer function). So this filter is a 2nd order IIR.

$$D := \begin{bmatrix} 1 & 1 \\ -2 & -\left(2 - F \cdot Q - F^2\right) \\ 1 & (1 - F \cdot Q) \end{bmatrix}$$

$$D = \begin{bmatrix} 1 & 1 \\ -2 & -1.777 \\ 1 & 0.858 \end{bmatrix}$$

Calculate gain compensation

$PK := \frac{4}{\left(4 - 2 \cdot F \cdot Q - F^2\right)}$

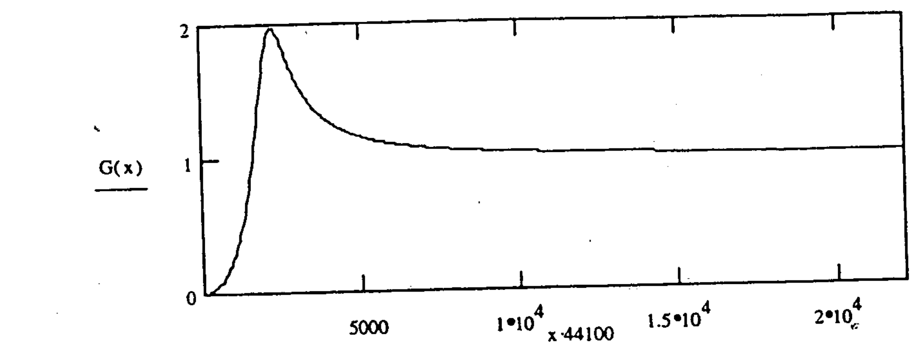
$K := \frac{1}{PK}$

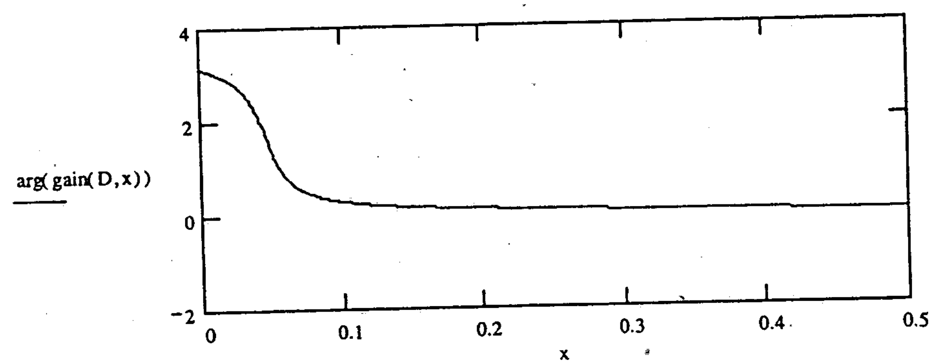
$K = 0.909$

Plot frequency and phase response of the filter

$x := 0, .001 .. .5$

$G(x) := K \cdot |gain(D, x)|$





Digital Low-Pass Filter Implementation #2 (one-zero)

Define sampling frequency

$Fs := 44100$

Define cutoff frequency

$Fc := 2000$

Normalized cutoff frequency

$fc := 2\cdot\frac{Fc}{Fs}$

$fc = 0.091$

Define Filter Q

$q := 10$

$Q := \frac{1}{q}$

Define Filter Parameters

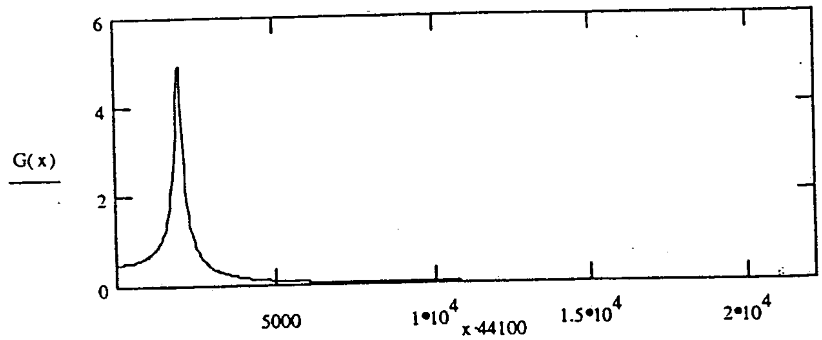
$F := 2\cdot\sin\left(fc\cdot\frac{\pi}{2}\right)$

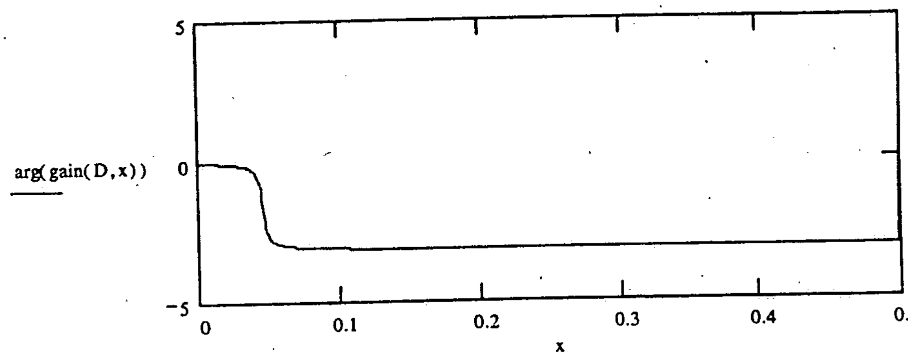
$F = 0.284$

$A := \frac{F^2}{2}$

$A = 0.04$

$B := A$





Define Transfer Function (1st column is numerator coefficients in transfer function and 2nd column is denominator coefficients in transfer function). So this filter is a 2nd order IIR.

$$D := \begin{bmatrix} 0 & 1 \\ B & -\left(2 - F\cdot Q - F^2\right) \\ 0 & (1 - F\cdot Q) \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 1 \\ 0.04 & -1.891 \\ 0 & 0.972 \end{bmatrix}$$

Plot frequency and phase response of the filter

$x := 0, .001 .. .5$

$G(x) := |\,gain(D, x)\,|$

FIG. A3

Digital Shelving EQ section based on an All-pass filter section

Define sampling frequency

$Fs := 44100$

Define critical frequency

$Fc := 10000$

Normalized critical frequency

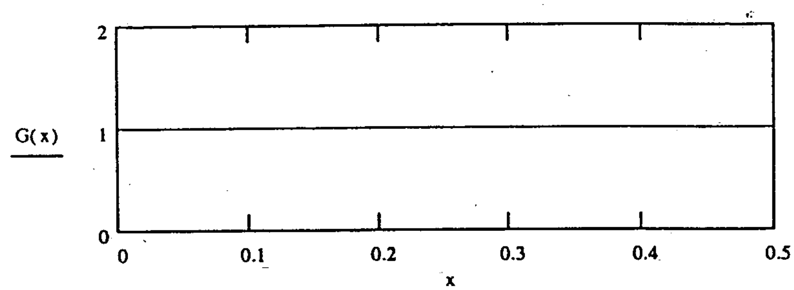
$$wc := 2\cdot\pi\cdot\frac{Fc}{Fs}$$

Define gain/cut

$k := 4$

Define Filter parameters

$$gamma := \frac{\left(\tan\left(\frac{wc}{2}\right) - 1\right)}{\left(\tan\left(\frac{wc}{2}\right) + 1\right)}$$



Define Transfer Function (1st column is numerator coefficients in transfer function and 2nd column is denominator coefficients in transfer function). So this filter is a 1st order IIR.

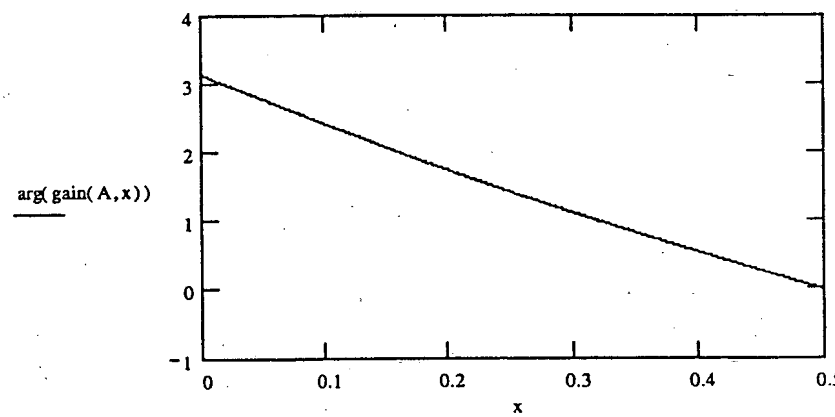
$$A := \begin{bmatrix} -gamma & 1 \\ -1 & gamma \end{bmatrix}$$

$$A = \begin{bmatrix} 0.073 & 1 \\ -1 & -0.073 \end{bmatrix}$$

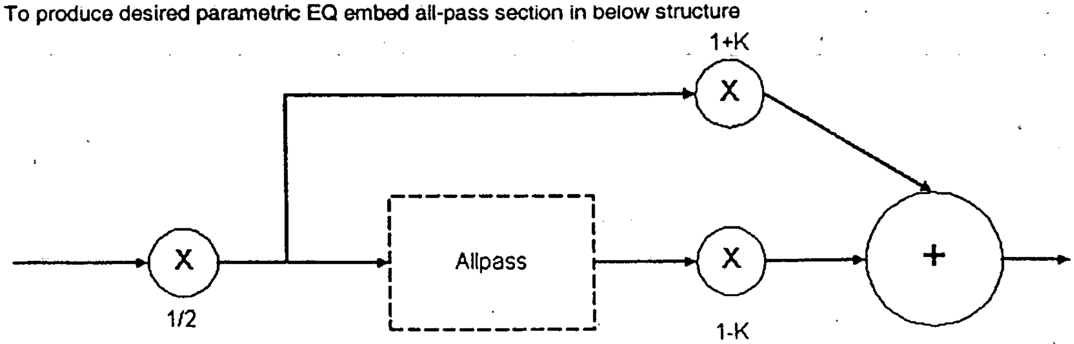
Plot frequency and phase response of the filter

$x := 0, .001 .. 0.5$

$G(x) := |\,gain(A, x)\,|$



To produce desired parametric EQ embed all-pass section in below structure



In a DSP implementation, the filter output is computed as per the above signal flow. Below we calculate the overall transfer function of the above system by transforming the numerator of the all-pass section as necessary.

FIG. A4 (Sheet 1 of 2)

$D := A$

$G := D^{<1>}$ extract denominator

$F := D^{<0>}$ extract numerator

$M := \frac{(1-k)}{2}$

$L := \frac{(1+k)}{2}$

build new numerator:

$F_0 := M \cdot F_0 + L$

$F_1 := M \cdot F_1 + L \cdot G_1$

$D^{<0>} := F$

$D = \begin{bmatrix} 2.39 & 1 \\ 1.317 & -0.073 \end{bmatrix}$

Plot magnitude response:

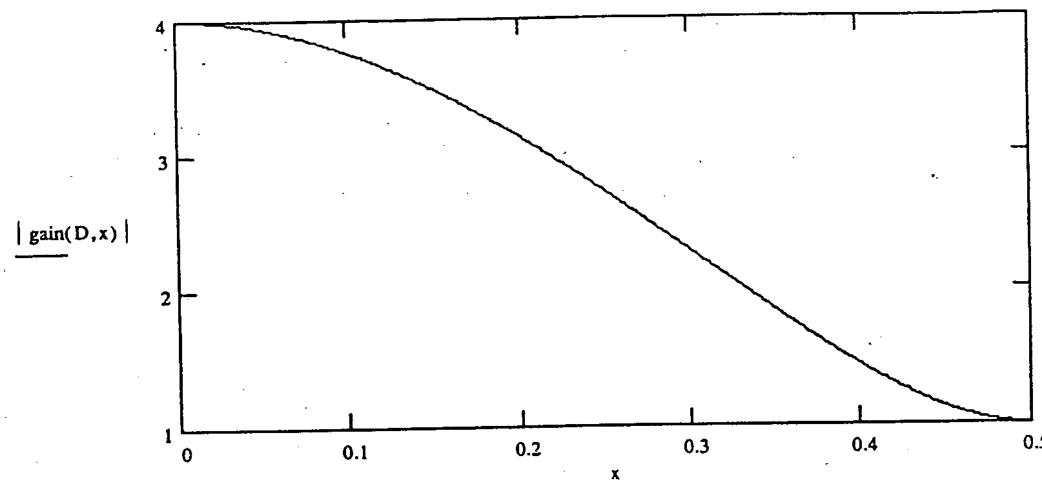


FIG. A4 (Sheet 2 of 2)

Digital Notch/Parametric EQ section based on an all-pass section

Define sampling frequency
$Fs := 44100$

Define critical frequency
$Fc := 5500$

Normalized critical frequency
$$wc := 2 \cdot \pi \cdot \frac{Fc}{Fs}$$

Define Filter Q
$Q := 4$

Define gain/cut
$k := 4$

Define Filter parameters
$gamma := -\cos(wc)$

$$fbeta := \frac{wc}{2 \cdot Q}$$

$$fbeta := if\left(fbeta > \frac{\pi}{4}, \frac{\pi}{4}, fbeta\right)$$

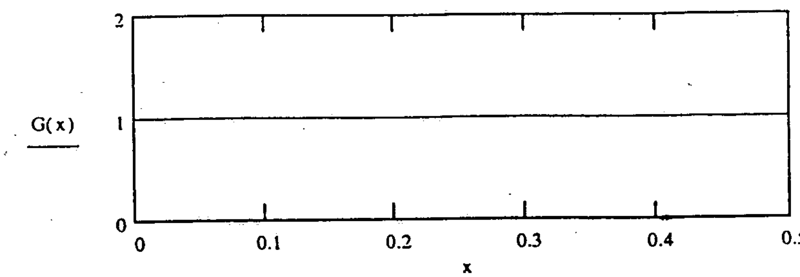
$$beta := \frac{1 - \tan(fbeta)}{1 + \tan(fbeta)}$$

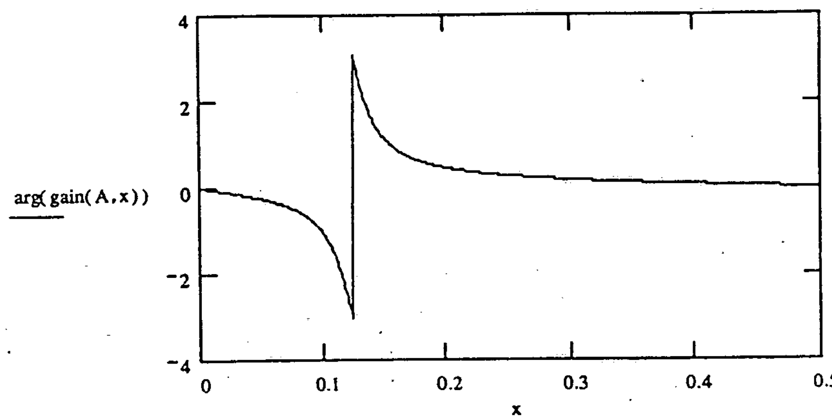
Define Transfer Function (1st column is numerator c
and 2nd column is denominator coefficients in transf
order IIR.

$$A := \begin{bmatrix} beta & 1 \\ gamma \cdot (1 + beta) & gamma \cdot (1 + beta) \\ 1 & beta \end{bmatrix}$$

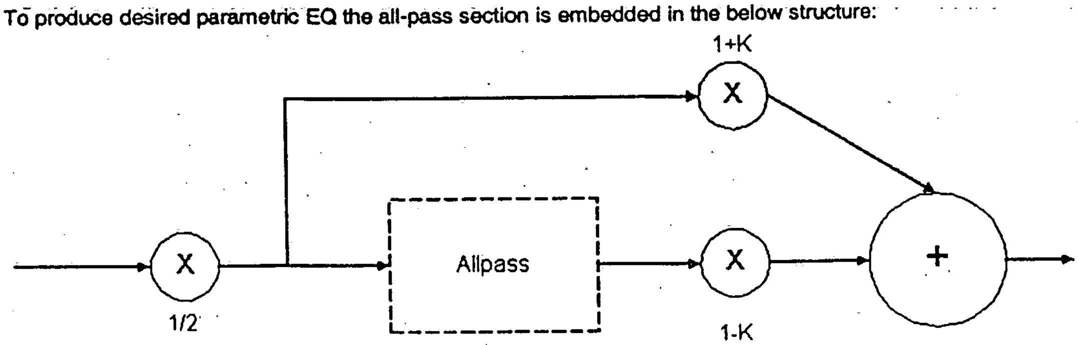
$$A = \begin{bmatrix} 0.821 & 1 \\ -1.29 & -1.29 \\ 1 & 0.821 \end{bmatrix}$$

Plot frequency and phase response of the filter
$x := 0, .001 .. 0.5$
$G(x) := |gain(A, x)|$





To produce desired parametric EQ the all-pass section is embedded in the below structure:



In a DSP implementation, the filter output is computed as per the above signal flow. Below we calculate the overall transfer function of the above system by

FIG. A5 (Sheet 1 of 2)

transforming the numerator of the all-pass section as necessary.

$D := A$

$G := D^{<1>}$ extract denominator

$F := D^{<0>}$ extract numerator

$M := \frac{(1-k)}{2}$

$L := \frac{(1+k)}{2}$

build new numerator:

$F_0 := M \cdot F_0 + L$

$F_1 := M \cdot F_1 + L \cdot G_1$

$F_2 := M \cdot F_2 + L \cdot G_2$

$D^{<0>} := F$

$$D = \begin{bmatrix} 1.268 & 1 \\ -1.29 & -1.29 \\ 0.553 & 0.821 \end{bmatrix}$$

Magnitude Response:

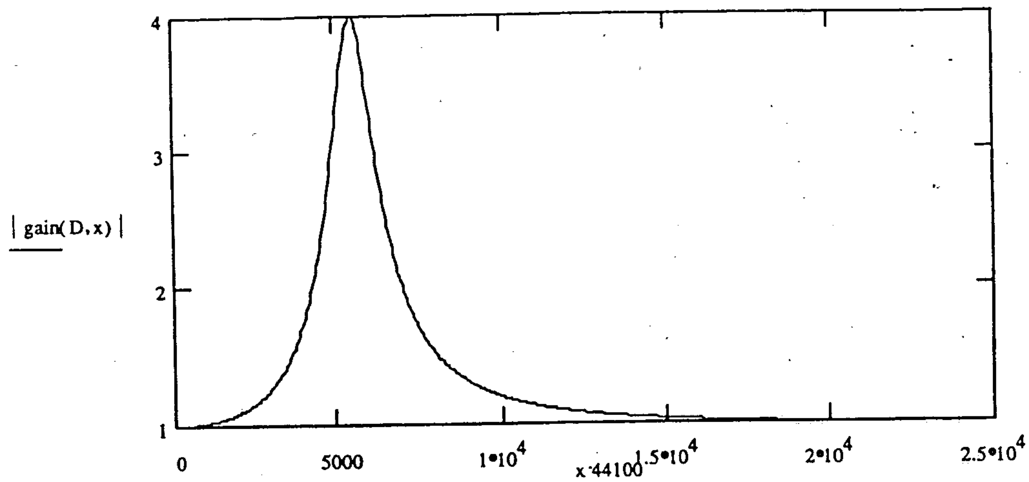


FIG. A5 (Sheet 2 of 2)

Digital Implementation of a Weighted Notch #1

Consists of 3 parametric EQ section designed using the procedure described in
"Notch/Parametric EQ section based on an all-pass section"

2 low Q gain section surround the critical frequency notch.

For compensation section #1 and #2 (D1 and D2 respectively) Q is 2 and k is 1.5 resulting in the below transfer functions. The resulting filters are two 2nd order IIR filters where column 0 represents the numerator and column 1 represents the denominator.

$$D1 := \begin{bmatrix} 1.076 & 1 \\ -1.283 & -1.283 \\ 0.619 & 0.695 \end{bmatrix}$$

$$D2 := \begin{bmatrix} 1.089 & 1 \\ -1.079 & -1.079 \\ 0.554 & 0.643 \end{bmatrix}$$

For critical frequency section #3 (D3 below) Q is 10 and k is 0. The resulting filter is a 2nd order IIR filters where column 0 represents the numerator and column 1 represents the denominator.

$$D3 := \begin{bmatrix} 0.962 & 1 \\ -1.363 & -1.363 \\ 0.962 & 0.925 \end{bmatrix}$$

Plot of the overall frequency response of the 3 IIR filters cascaded

$x := 0, .001 .. 0.5$
$G1(x) := |\,gain(D1, x)\,|$
$G2(x) := |\,gain(D2, x)\,|$
$G3(x) := |\,gain(D3, x)\,|$
$H(x) := 20 \cdot \log(G1(x) \cdot G2(x) \cdot G3(x))$

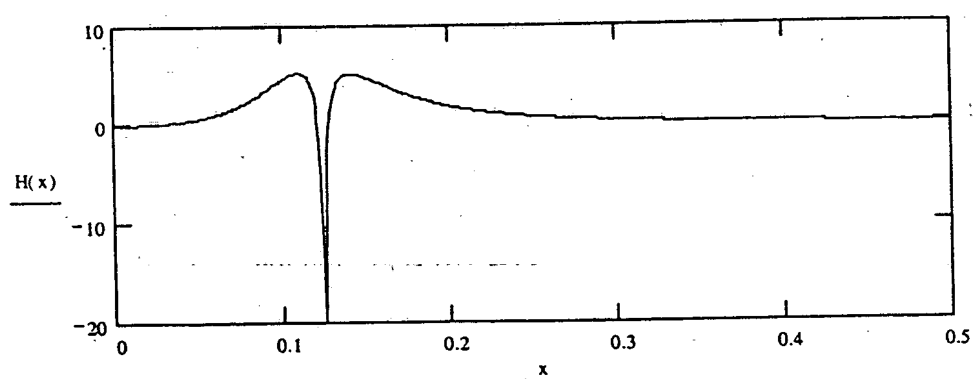


FIG. A6

Digital Implementation of a Weighted Notch #2

Consists of 3 parametric EQ section designed using the procedure described in
"Notch/Parametric EQ section based on an all-pass section"

One medium Q gain compensation section centered around two notches.

For compensation section #1 (D1 below) Q is 4 and k is 4 resulting in the below transfer function. The resulting filters is a 2nd order IIR filters where column 0 represents the numerator and column 1 represents the denominator.

$$D1 := \begin{bmatrix} 1.268 & 1 \\ -1.29 & -1.29 \\ 0.553 & 0.821 \end{bmatrix}$$

For critical frequency notches sections #2 and #3 (D2 and D3 below respectively) Q is 10 and k is 0. The resulting filters are two 2nd order IIR filters where column 0 represents the numerator and column 1 represents the denominator.

$$D2 := \begin{bmatrix} 0.963 & 1 \\ -1.383 & -1.383 \\ 0.963 & 0.926 \end{bmatrix}$$

$$D3 := \begin{bmatrix} 0.962 & 1 \\ -1.343 & -1.343 \\ 0.962 & 0.923 \end{bmatrix}$$

Plot of the overall frequency response of the 3 IIR filters cascaded:

$x := 0, .0001 .. 0.5$

$G1(x) := | \mathrm{gain}(D1, x) |$

$G2(x) := | \mathrm{gain}(D2, x) |$

$G3(x) := | \mathrm{gain}(D3, x) |$

$H(x) := 20 \cdot \log(G1(x) \cdot G2(x) \cdot G3(x))$ (cascaded response)

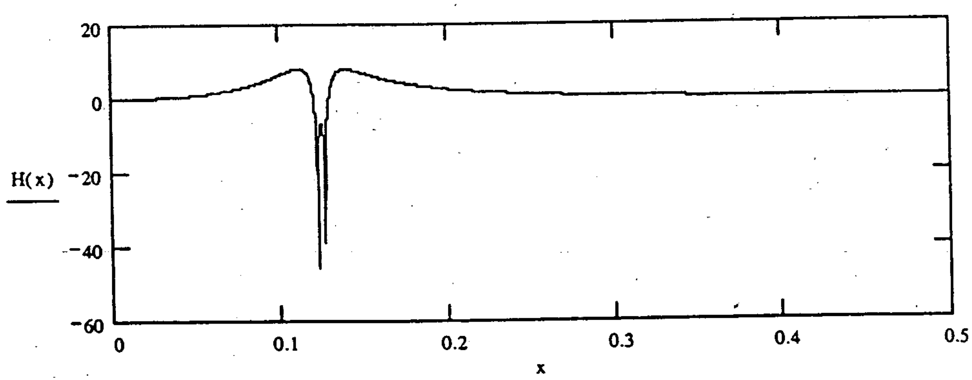


FIG. A7

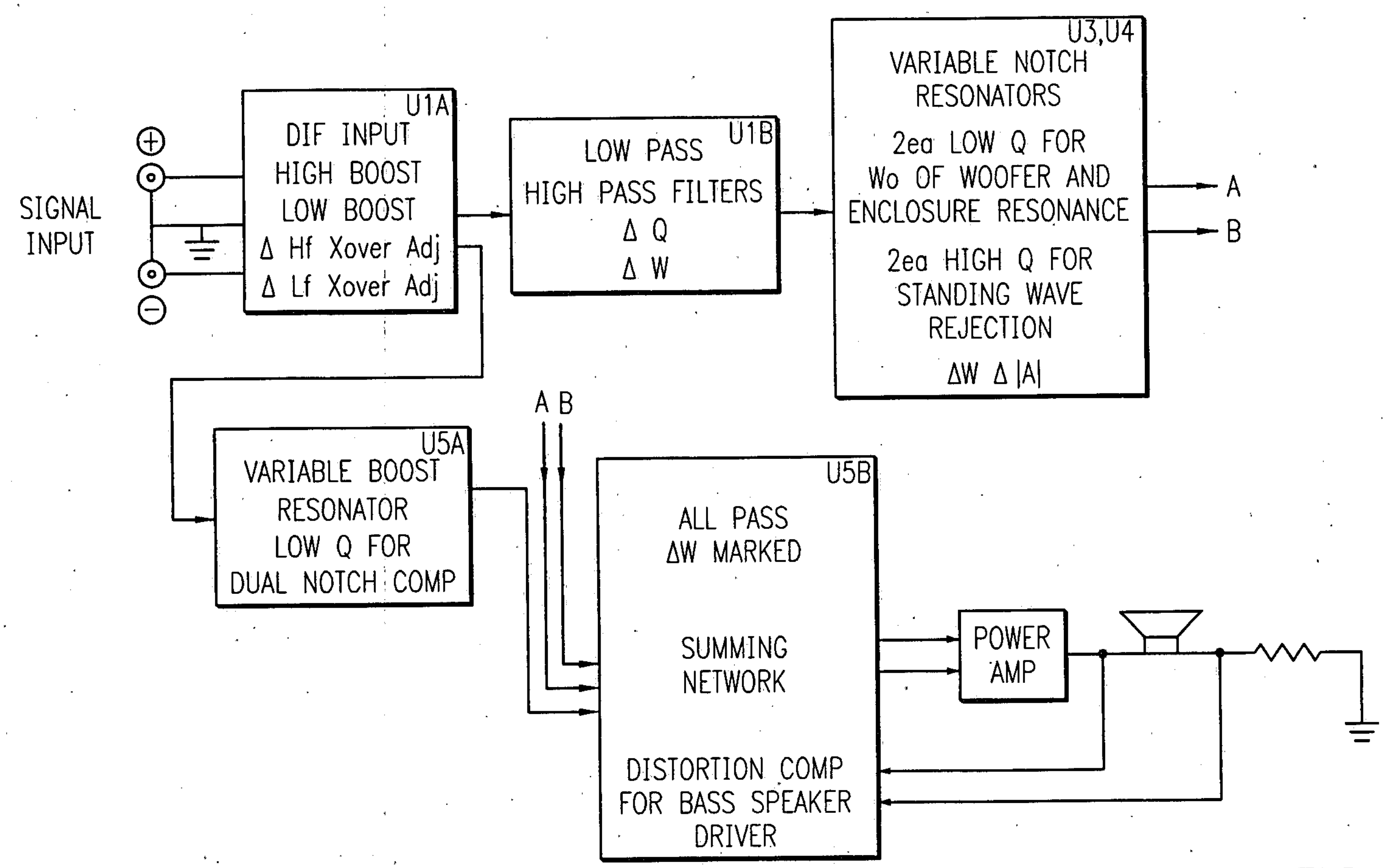

SIGNAL INPUT
U1A
DIF INPUT
HIGH BOOST
LOW BOOST
Δ Hf Xover Adj
Δ Lf Xover Adj
U1B
LOW PASS
HIGH PASS FILTERS
Δ Q
Δ W
U3,U4
VARIABLE NOTCH RESONATORS
2ea LOW Q FOR Wo OF WOOFER AND ENCLOSURE RESONANCE
2ea HIGH Q FOR STANDING WAVE REJECTION
ΔW Δ |A|
A
B
U5A
VARIABLE BOOST RESONATOR LOW Q FOR DUAL NOTCH COMP
A B
U5B
ALL PASS
ΔW MARKED
SUMMING NETWORK
DISTORTION COMP FOR BASS SPEAKER DRIVER
POWER AMP

FIG. B1

SLOPE EQ AND BANDPASS FILTER ADJUSTED
W_L=65Hz, 44Hz (PARALLEL CAPS)
W_H=17kHz
W_{LX}=400Hz -> 20Hz
W_{HX}=3kHz -> 25kHz

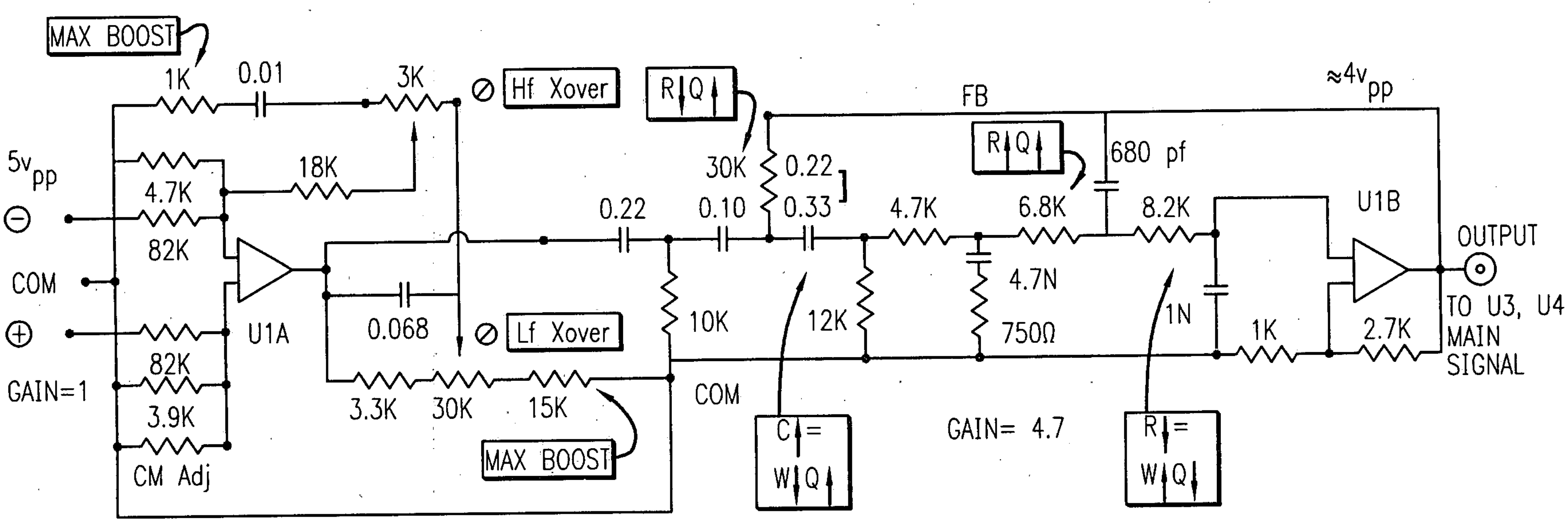
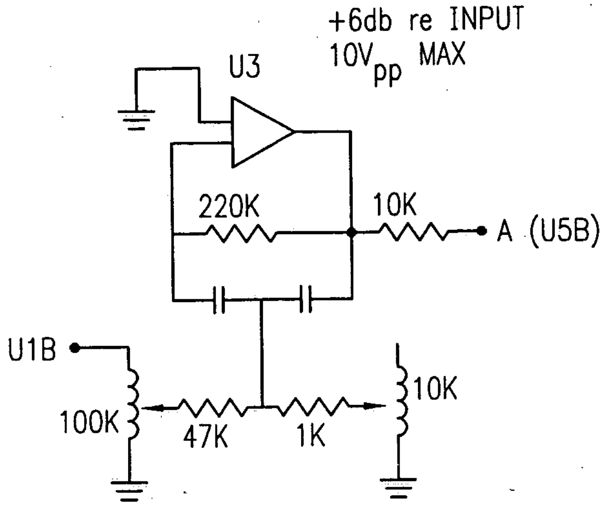


FIG. B2

FIG. B3



0.0015=3.2–3.6k (2.5k–>6.8k)
0.0033=1.4–>1.7k (1.2k–>3.3k)
0.0047≅900–1.2k (800–>2.2k)
0.15=120 (80–220)

LOWQ R|A|=47k||33k
RQ=68k||100k

$V_{OUT}=10V_{pp}$ MAX
(+6dB)

FIG. B4

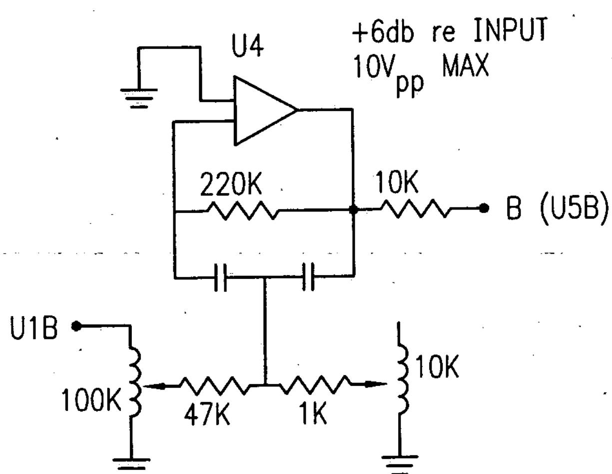
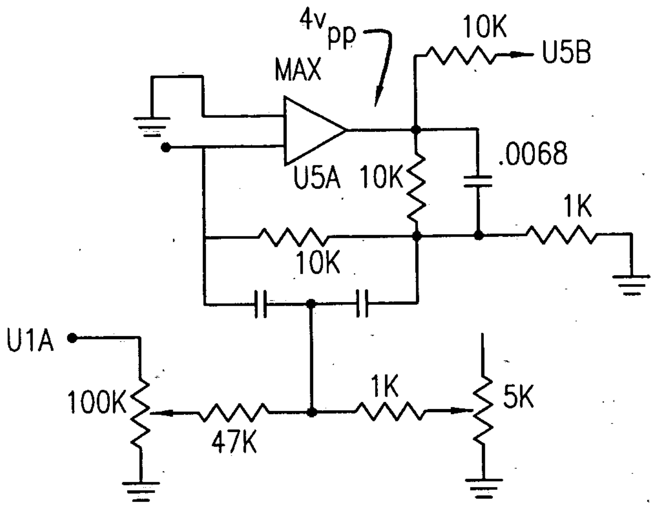


FIG. B5



0.033=270->1.4k
0.0068
700Hz opt
@ 3/4 max W_0

FIG. B6

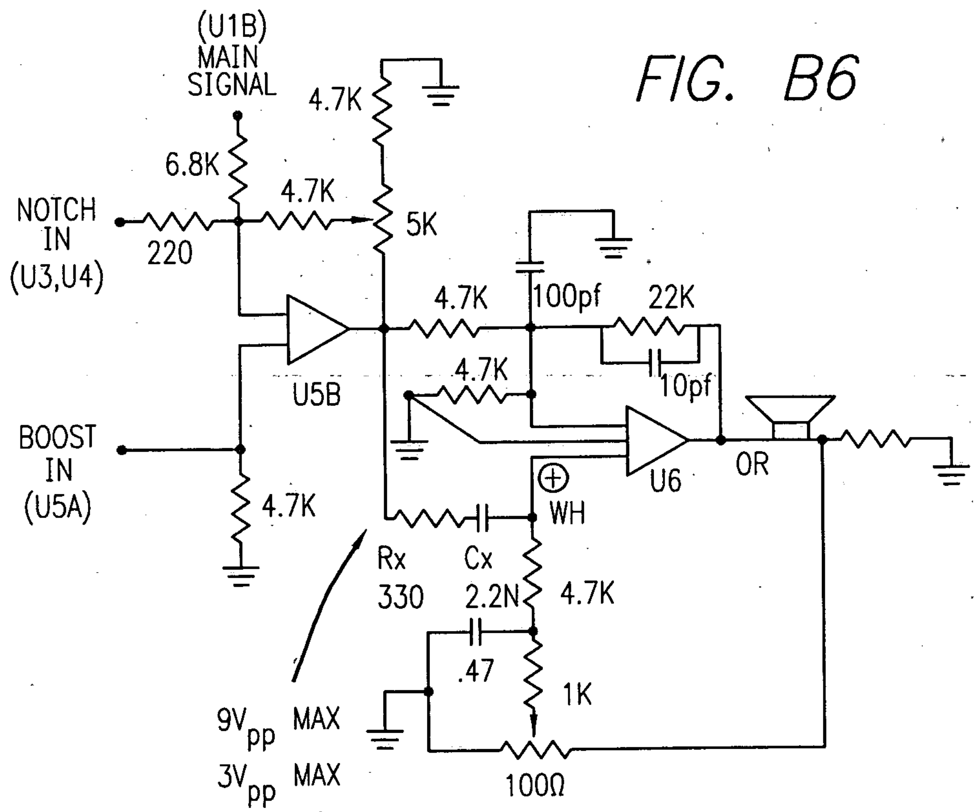
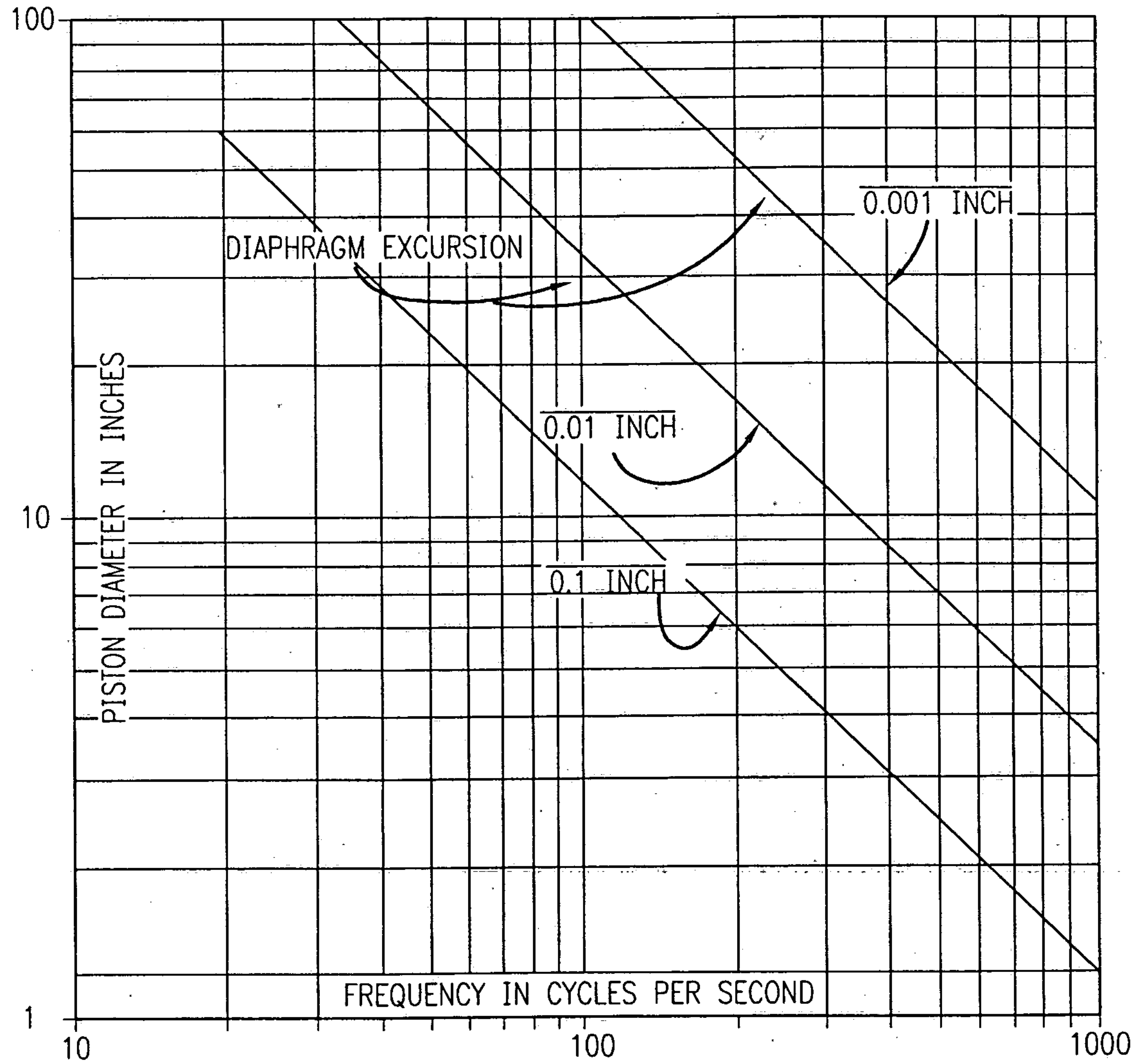
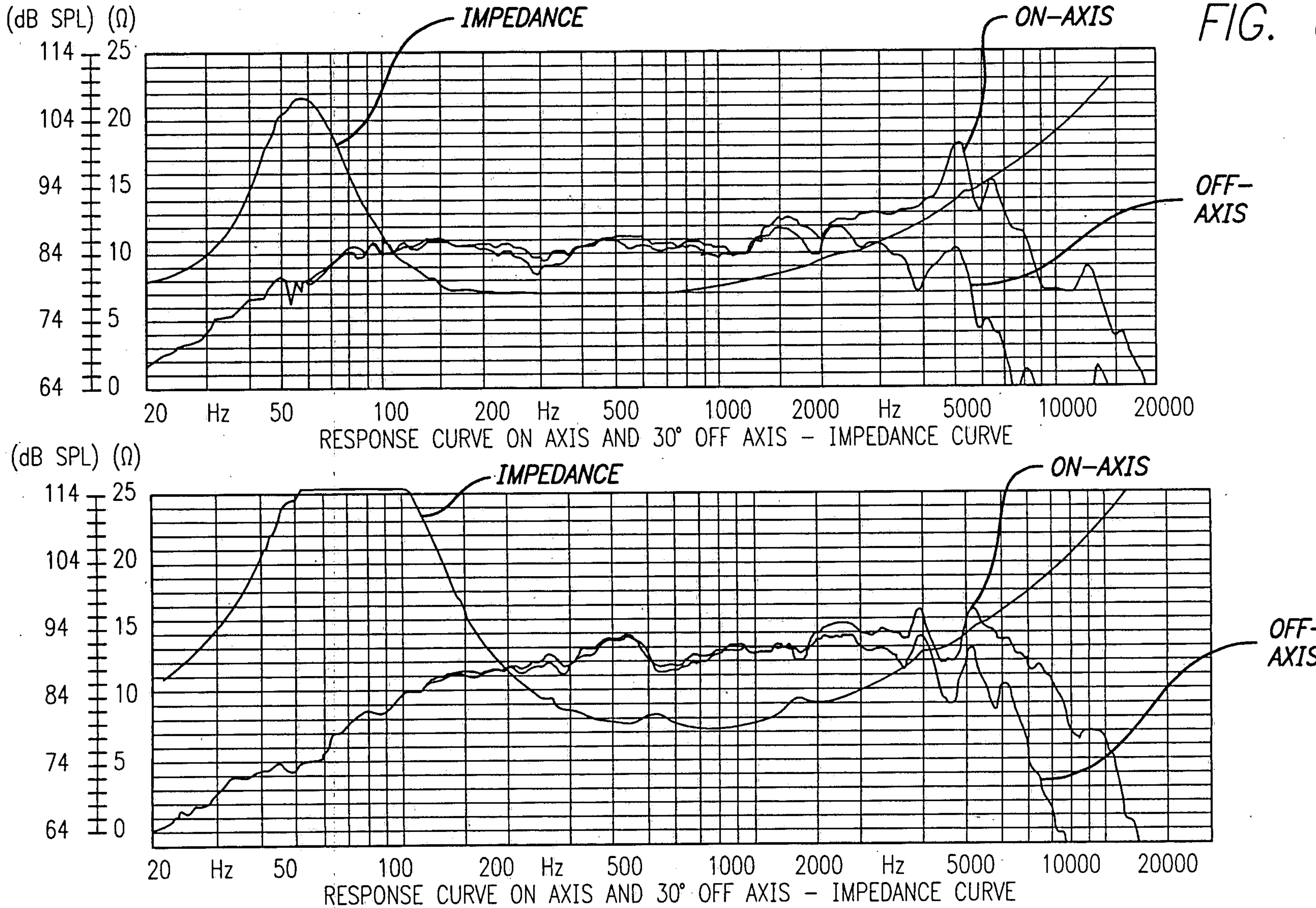


FIG. 5



100
10
1
10
100
1000
PISTON DIAMETER IN INCHES
FREQUENCY IN CYCLES PER SECOND
DIAPHRAGM EXCURSION
0.001 INCH
0.01 INCH
0.1 INCH

FIG. 6



(dB SPL) (Ω)
114
104
94
84
74
64
25
20
15
10
5
0
IMPEDANCE
ON-AXIS
OFF-AXIS
20
Hz
50
100
200
Hz
500
1000
2000
Hz
5000
10000
20000
RESPONSE CURVE ON AXIS AND 30° OFF AXIS - IMPEDANCE CURVE
(dB SPL) (Ω)
114
104
94
84
74
64
25
20
15
10
5
0
IMPEDANCE
ON-AXIS
OFF-AXIS
20
Hz
50
100
200
Hz
500
1000
2000
Hz
5000
10000
20000
RESPONSE CURVE ON AXIS AND 30° OFF AXIS - IMPEDANCE CURVE

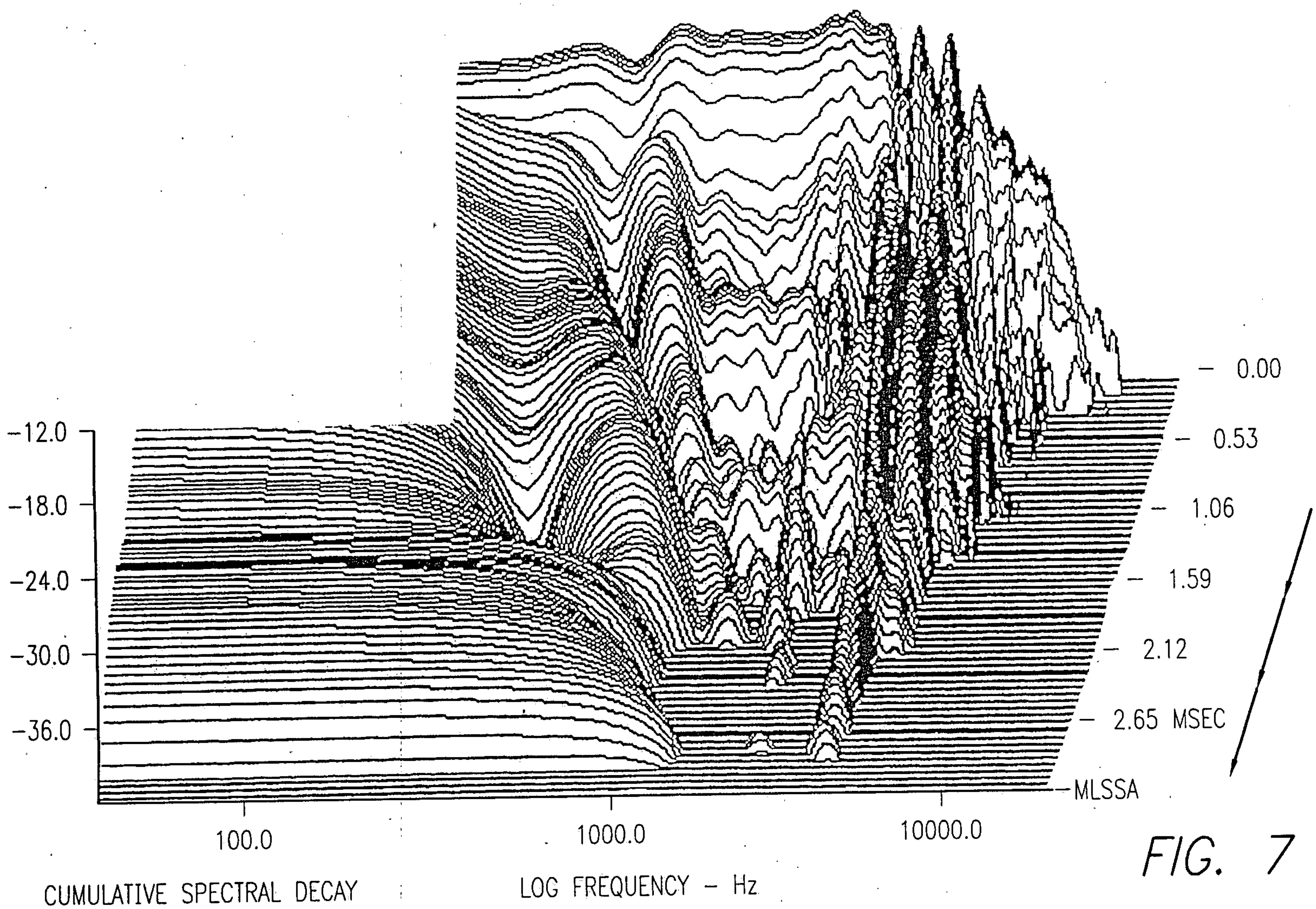

-12.0
-18.0
-24.0
-30.0
-36.0
100.0
1000.0
10000.0
CUMULATIVE SPECTRAL DECAY
LOG FREQUENCY - Hz
0.00
0.53
1.06
1.59
2.12
2.65 MSEC
MLSSA

FIG. 7

FIG. 8a

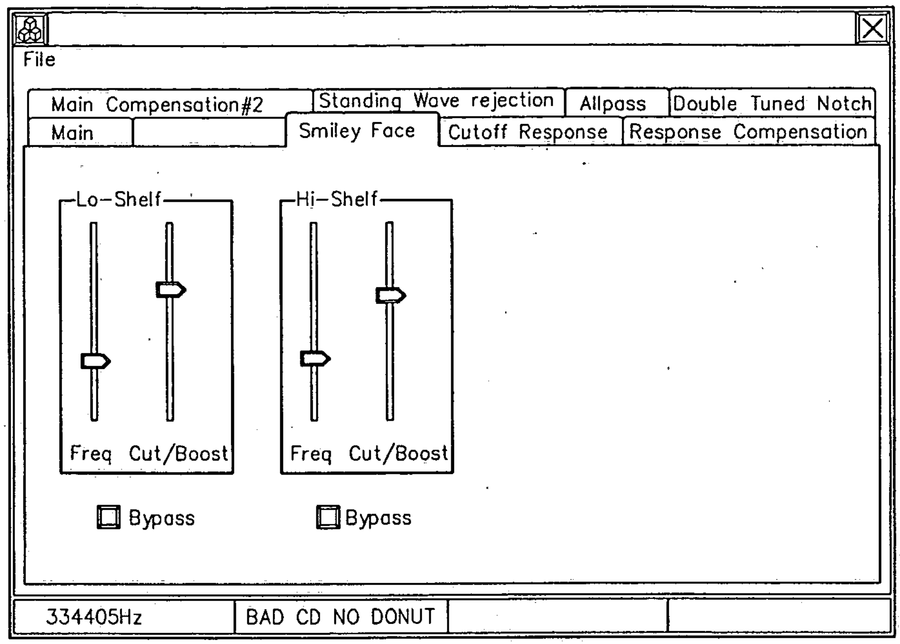

File
Main Compensation#2
Standing Wave rejection
Allpass
Double Tuned Notch
Main
Smiley Face
Cutoff Response
Response Compensation
Lo-Shelf
Freq
Cut/Boost
Bypass
Hi-Shelf
Freq
Cut/Boost
Bypass
334405Hz
BAD CD NO DONUT

FIG. 8b

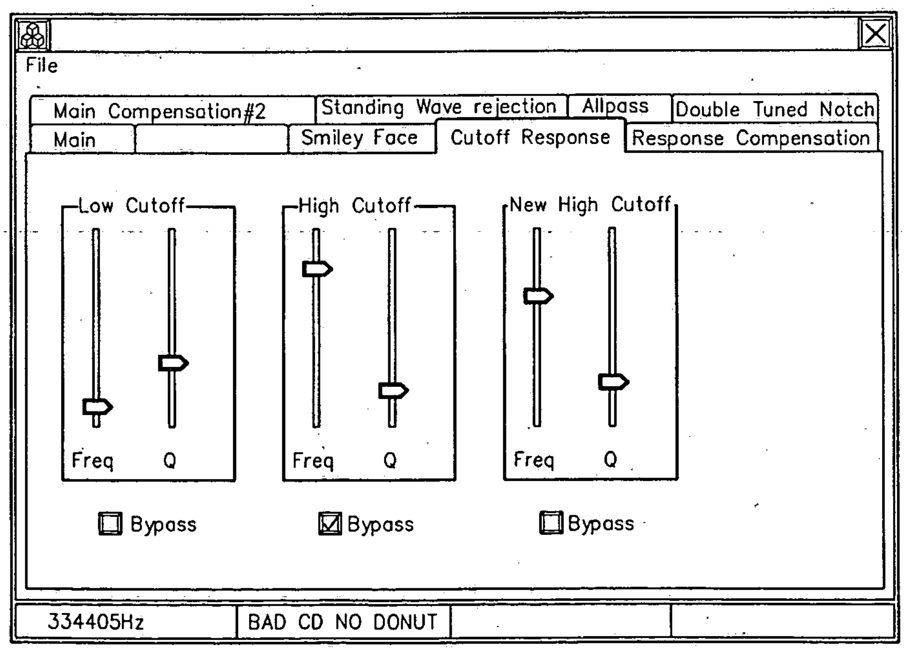

File
Main Compensation#2
Standing Wave rejection
Allpass
Double Tuned Notch
Main
Smiley Face
Cutoff Response
Response Compensation
Low Cutoff
Freq
Q
Bypass
High Cutoff
Freq
Q
Bypass
New High Cutoff
Freq
Q
Bypass
334405Hz
BAD CD NO DONUT

FIG. 8c

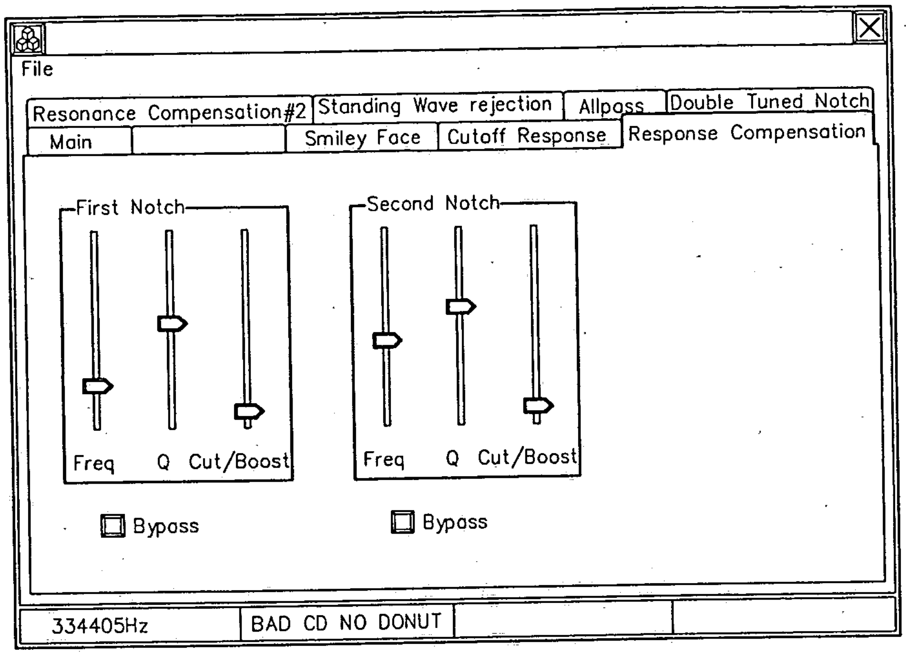

File
Resonance Compensation#2
Standing Wave rejection
Allpass
Double Tuned Notch
Main
Smiley Face
Cutoff Response
Response Compensation
First Notch
Freq
Q
Cut/Boost
Second Notch
Freq
Q
Cut/Boost
Bypass
Bypass
334405Hz
BAD CD NO DONUT

FIG. 8d

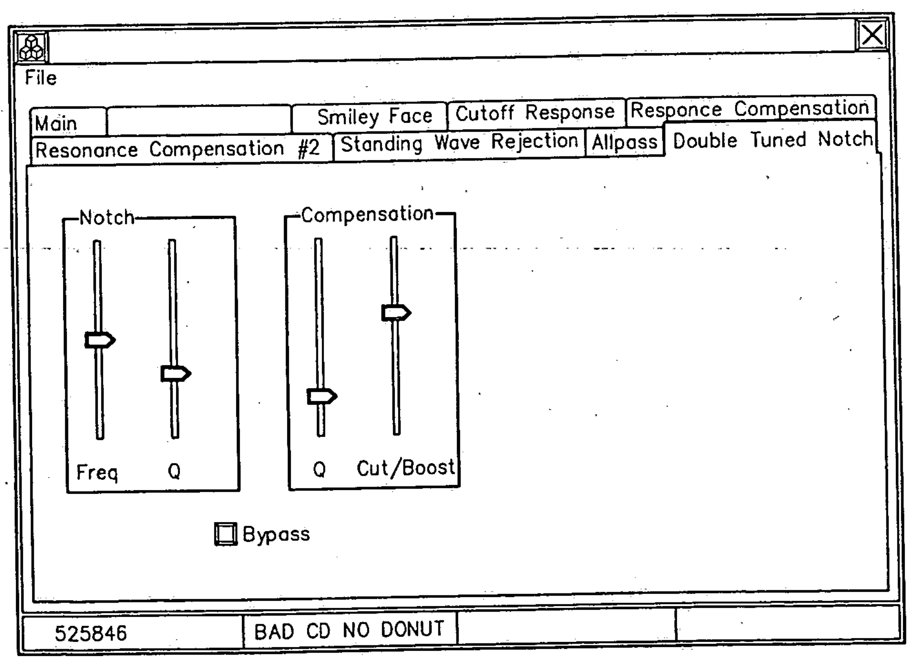

File
Main
Smiley Face
Cutoff Response
Responce Compensation
Resonance Compensation #2
Standing Wave Rejection
Allpass
Double Tuned Notch
Notch
Freq
Q
Compensation
Q
Cut/Boost
Bypass
525846
BAD CD NO DONUT

FIG. 8e

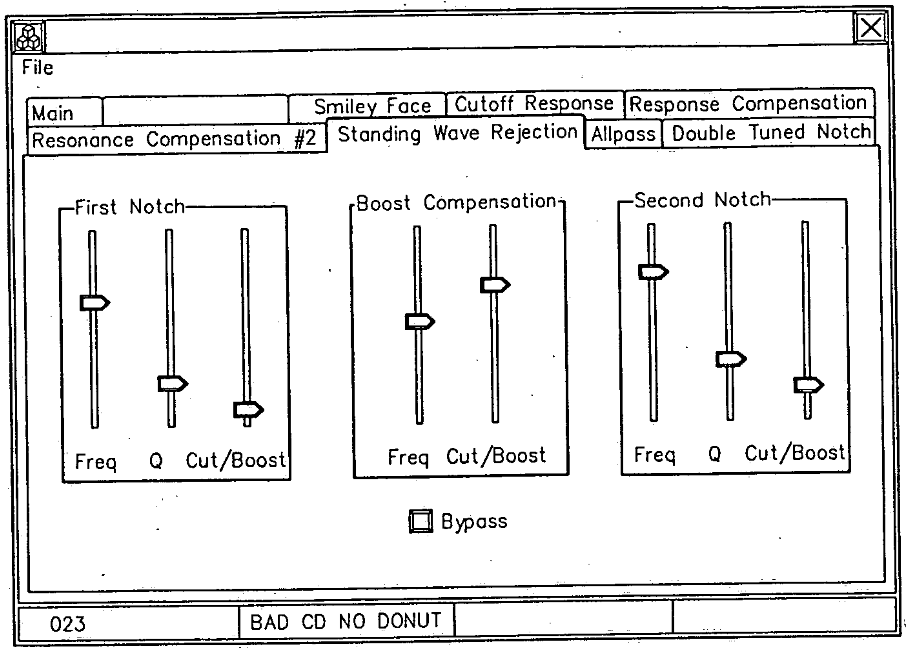

File
Main
Smiley Face
Cutoff Response
Response Compensation
Resonance Compensation #2
Standing Wave Rejection
Allpass
Double Tuned Notch
First Notch
Freq
Q
Cut/Boost
Boost Compensation
Freq
Cut/Boost
Second Notch
Freq
Q
Cut/Boost
Bypass
023
BAD CD NO DONUT

FIG. 8f

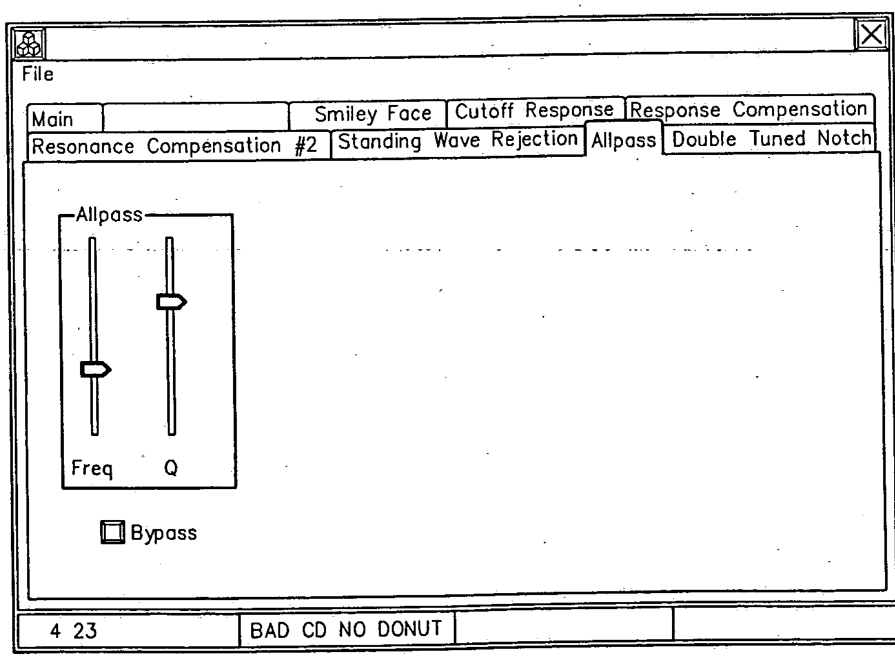
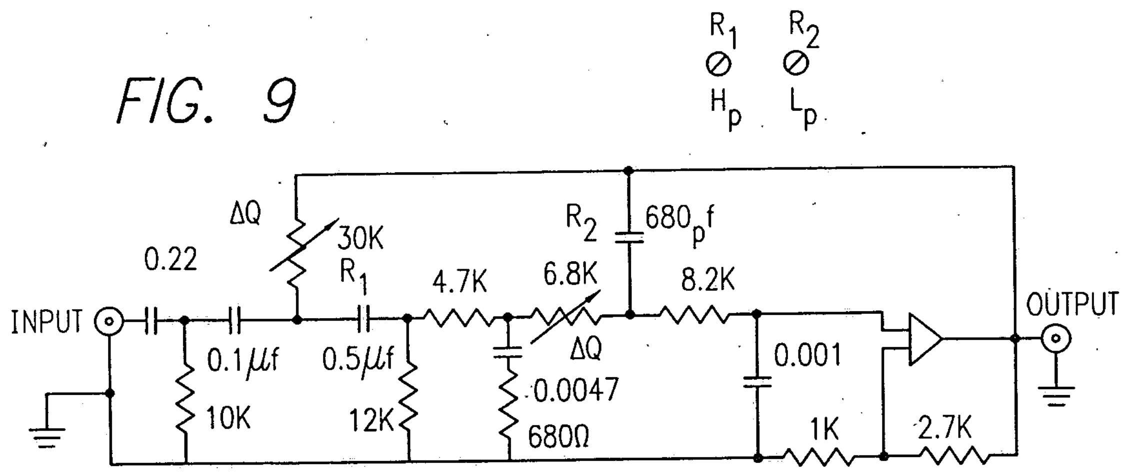
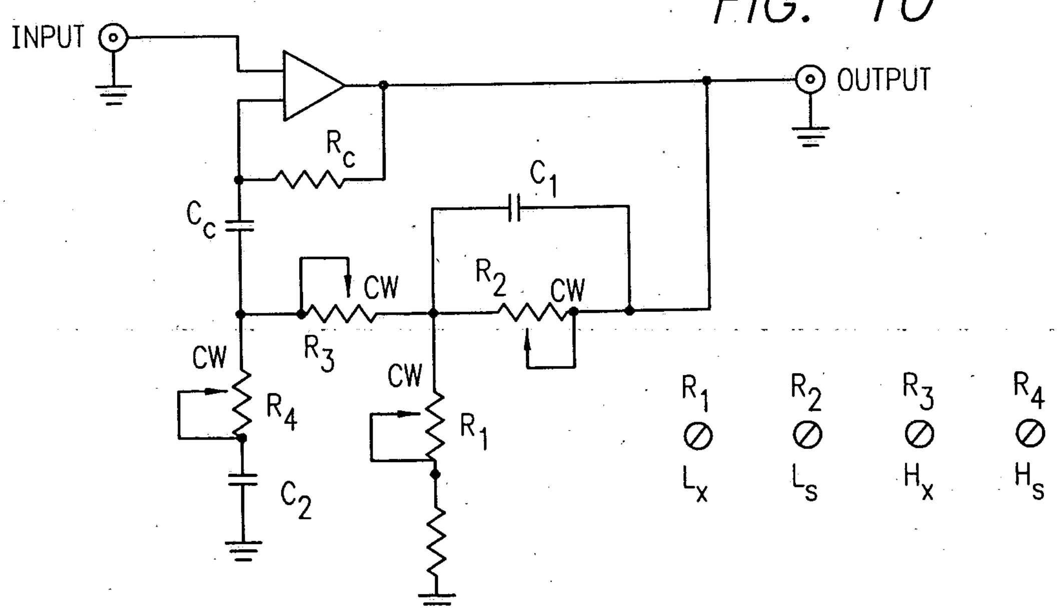

File
Main
Smiley Face
Cutoff Response
Response Compensation
Resonance Compensation #2
Standing Wave Rejection
Allpass
Double Tuned Notch
Allpass
Freq
Q
Bypass
4 23
BAD CD NO DONUT

FIG. 9



R1
Hp
R2
Lp
ΔQ
30K
R1
0.22
INPUT
0.1μf
10K
0.5μf
12K
4.7K
R2
680pf
6.8K
ΔQ
0.0047
680Ω
8.2K
0.001
1K
2.7K
OUTPUT

FIG. 10



INPUT
OUTPUT
Rc
Cc
C1
CW
R3
R2
CW
CW
R4
C2
CW
R1
R1
Lx
R2
Ls
R3
Hx
R4
Hs

FIG. 11

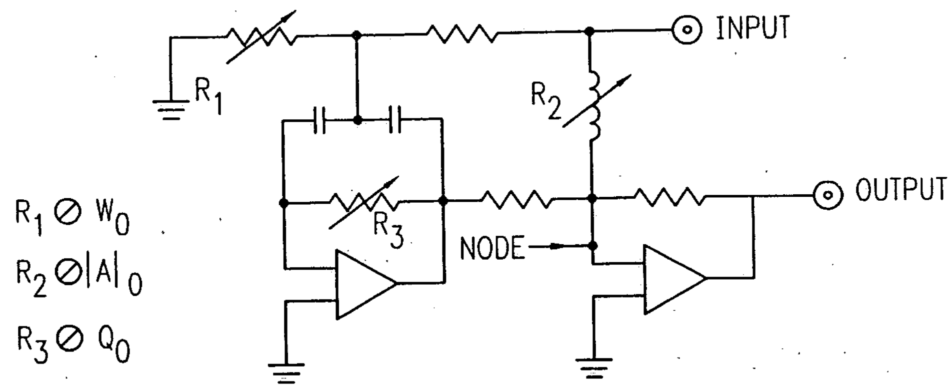
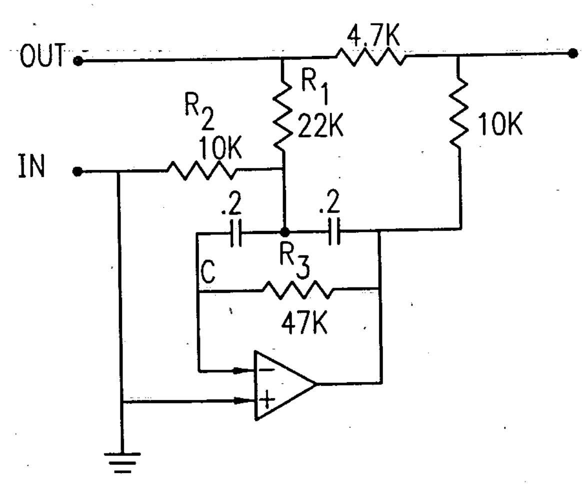

INPUT
R1
R2
R3
OUTPUT
NODE
R1 ⊘ W0
R2 ⊘ |A| 0
R3 ⊘ Q0

FIG. 12


OUT
4.7K
R1
22K
R2
10K
10K
IN
.2
.2
R3
C
47K
−
+

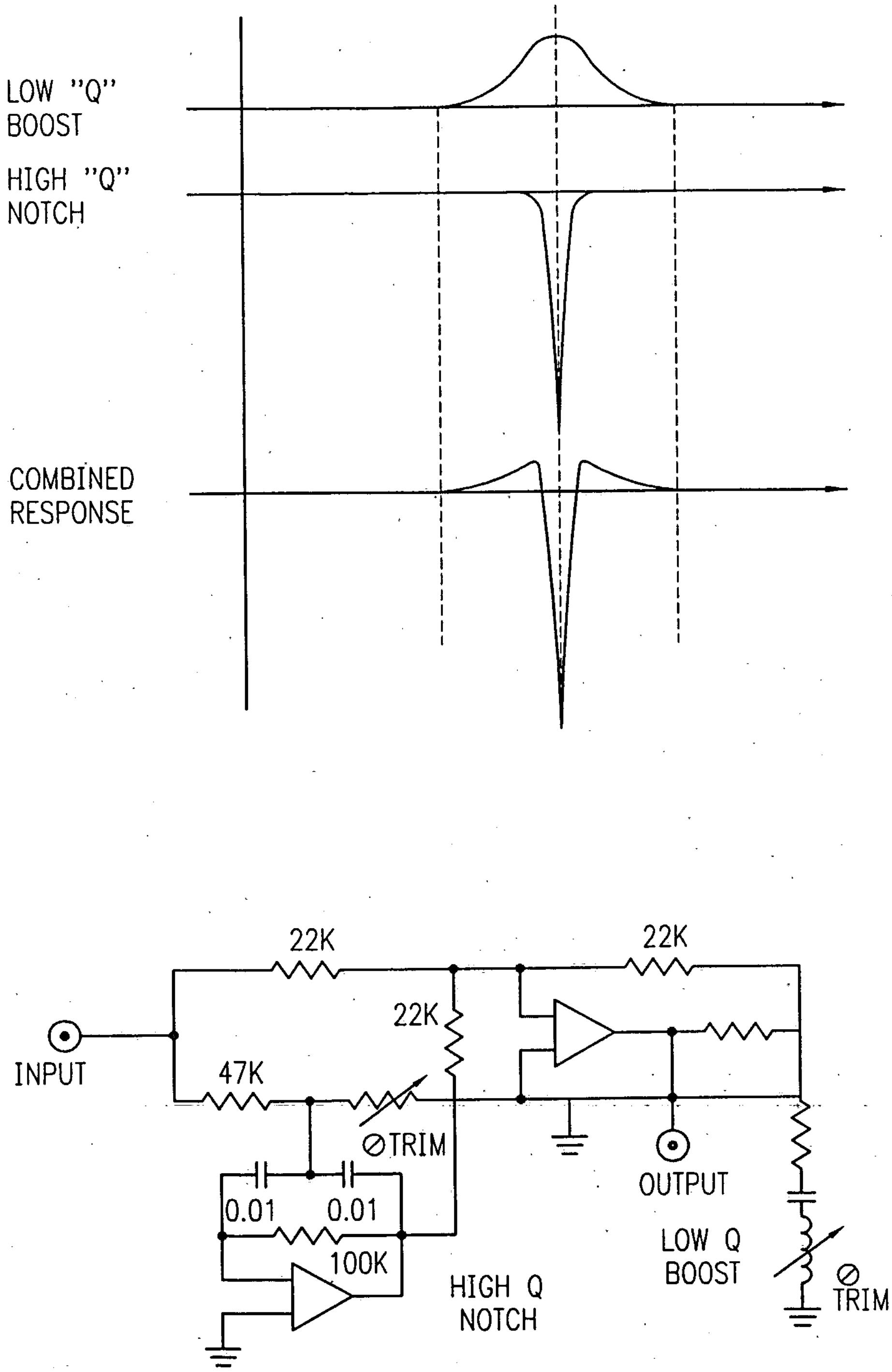

LOW "Q" BOOST
HIGH "Q" NOTCH
COMBINED RESPONSE
22K
22K
22K
INPUT
47K
⊘TRIM
0.01
0.01
100K
HIGH Q NOTCH
OUTPUT
LOW Q BOOST
⊘ TRIM

FIG. 13

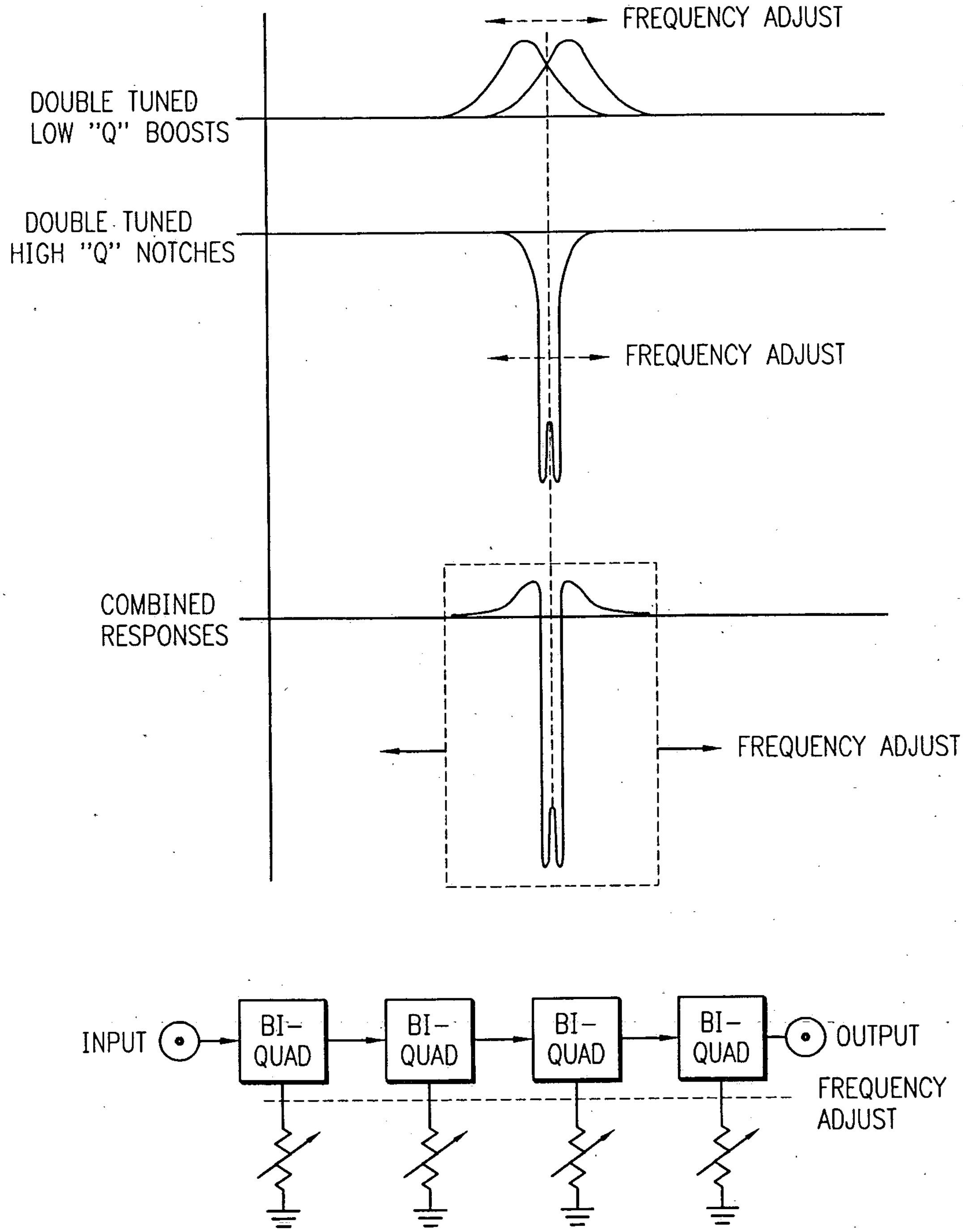

FREQUENCY ADJUST
DOUBLE TUNED
LOW "Q" BOOSTS
DOUBLE TUNED
HIGH "Q" NOTCHES
FREQUENCY ADJUST
COMBINED
RESPONSES
FREQUENCY ADJUST
INPUT
BI-
QUAD
BI-
QUAD
BI-
QUAD
BI-
QUAD
OUTPUT
FREQUENCY
ADJUST

FIG. 14

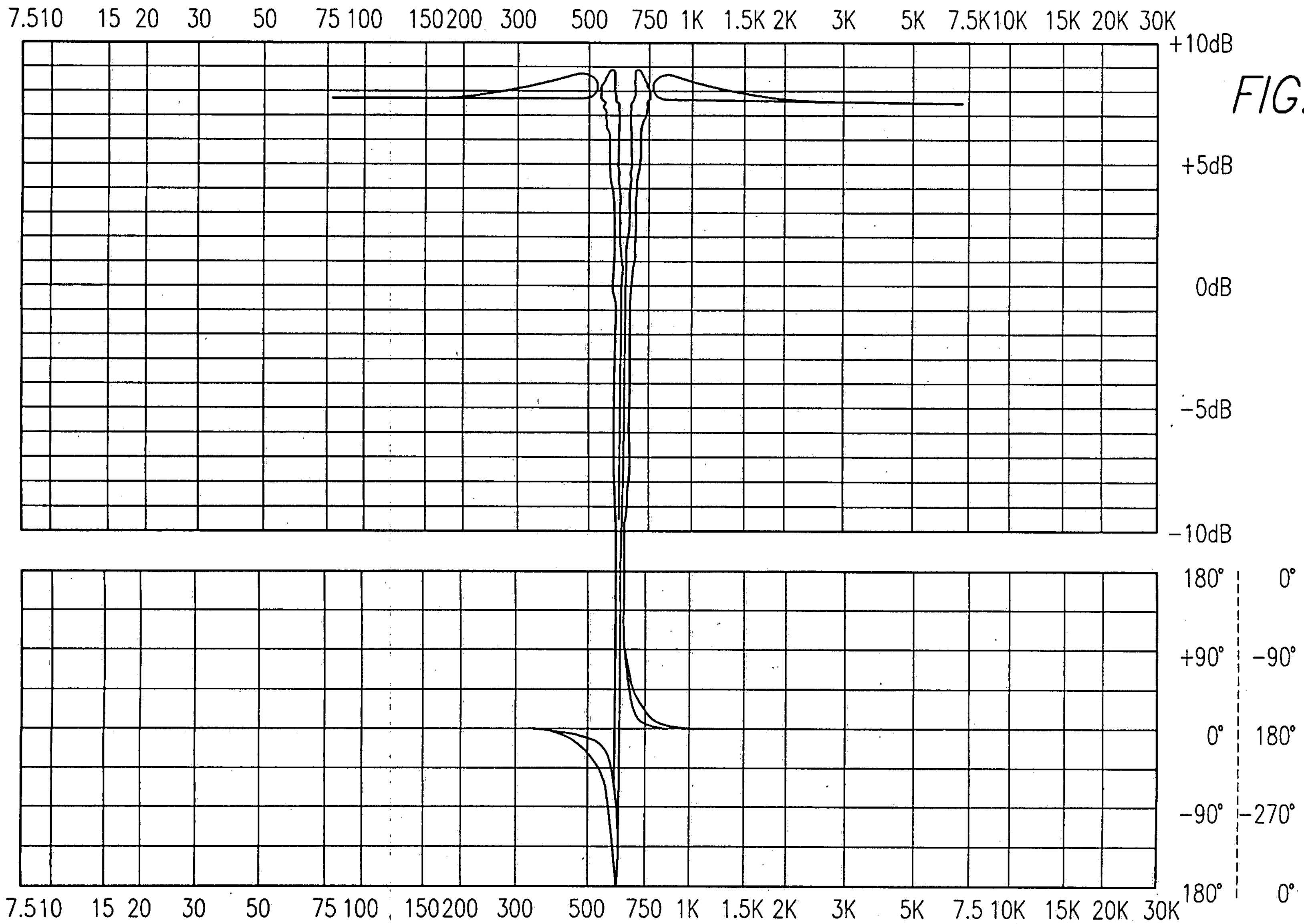

7.5 10 15 20 30 50 75 100 150 200 300 500 750 1K 1.5K 2K 3K 5K 7.5K 10K 15K 20K 30K
+10dB
+5dB
0dB
-5dB
-10dB
180° 0°
+90° -90°
0° 180°
-90° -270°
180° 0°

FIG. 15

FIG. 16

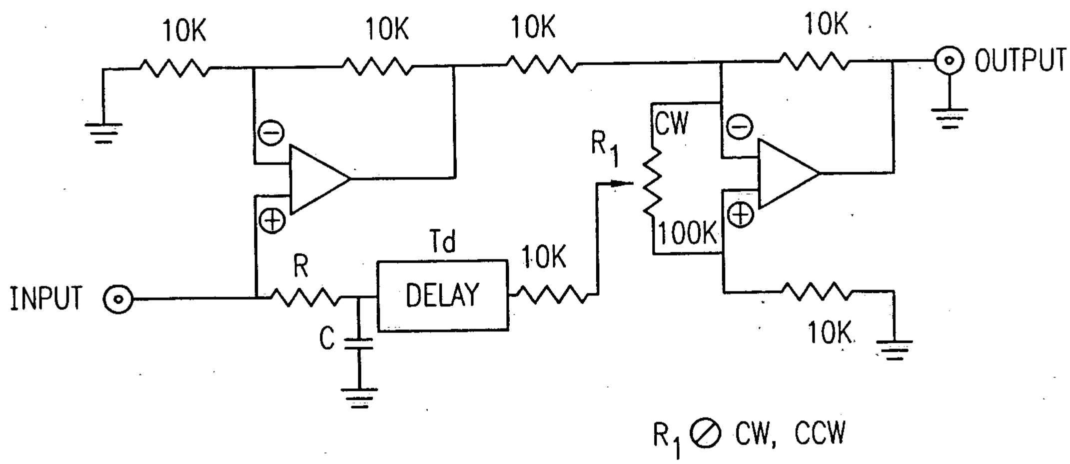
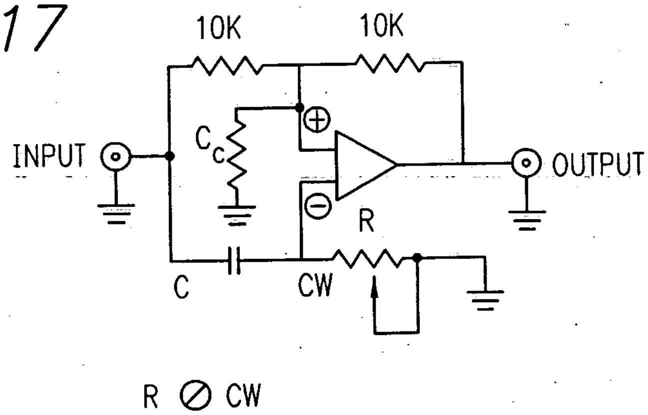

10K
10K
10K
10K
OUTPUT
CW
R1
100K
Td
DELAY
R
10K
INPUT
C
10K
R1 ⊘ CW, CCW

FIG. 17


10K
10K
INPUT
Cc
OUTPUT
R
C
CW
R ⊘ CW

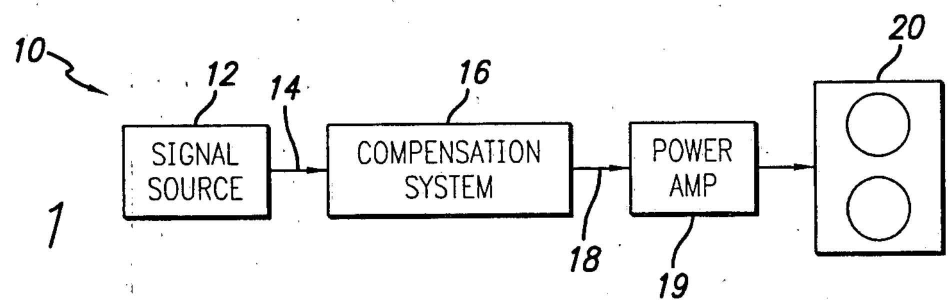

10
12
SIGNAL SOURCE
14
16
COMPENSATION SYSTEM
18
POWER AMP
19
20

FIG. 1

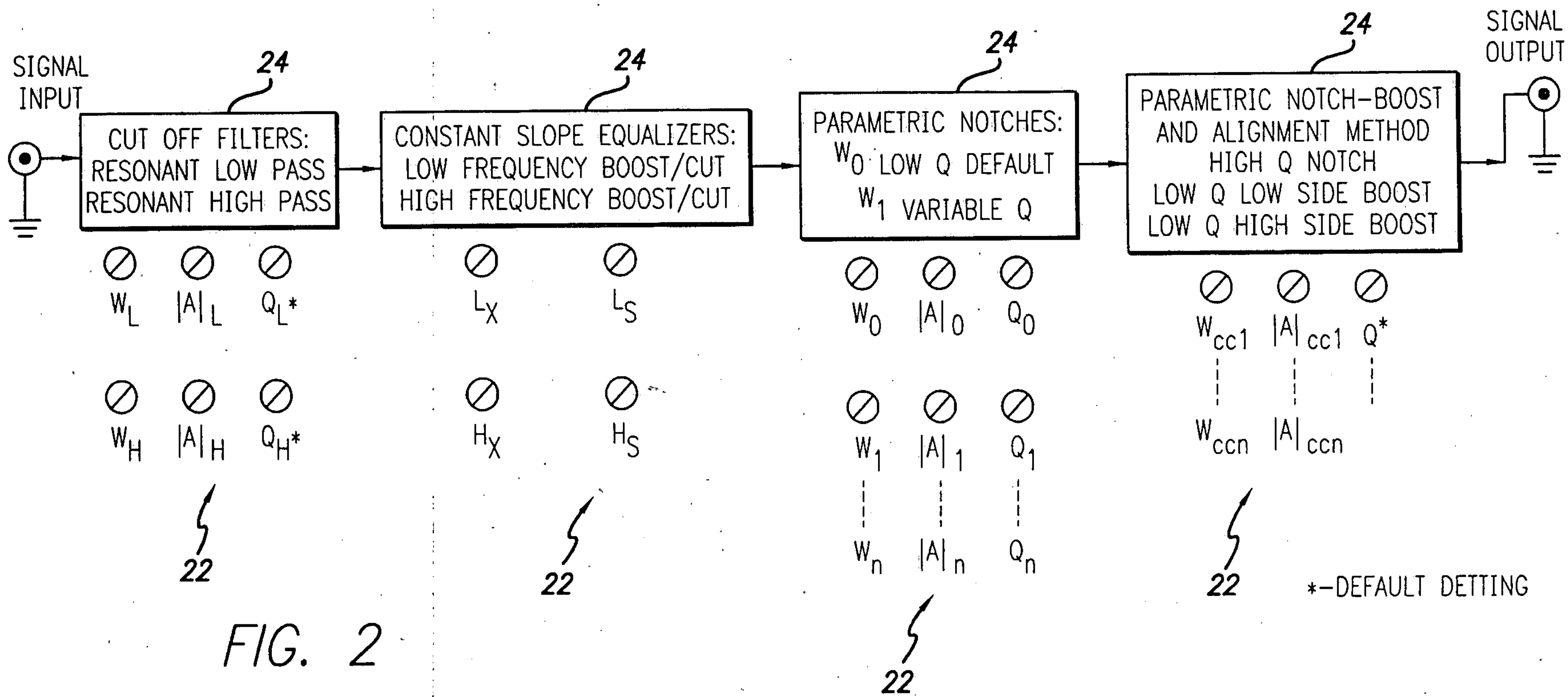

SIGNAL INPUT
24
CUT OFF FILTERS:
RESONANT LOW PASS
RESONANT HIGH PASS
W_L $|A|_L$ Q_L*
W_H $|A|_H$ Q_H*
22
24
CONSTANT SLOPE EQUALIZERS:
LOW FREQUENCY BOOST/CUT
HIGH FREQUENCY BOOST/CUT
L_X L_S
H_X H_S
22
24
PARAMETRIC NOTCHES:
W_0 LOW Q DEFAULT
W_1 VARIABLE Q
W_0 $|A|_0$ Q_0
W_1 $|A|_1$ Q_1
W_n $|A|_n$ Q_n
22
24
PARAMETRIC NOTCH-BOOST
AND ALIGNMENT METHOD
HIGH Q NOTCH
LOW Q LOW SIDE BOOST
LOW Q HIGH SIDE BOOST
W_{cc1} $|A|_{cc1}$ Q*
W_{ccn} $|A|_{ccn}$
22
SIGNAL OUTPUT
*–DEFAULT DETTING

FIG. 2

FIG. 3a

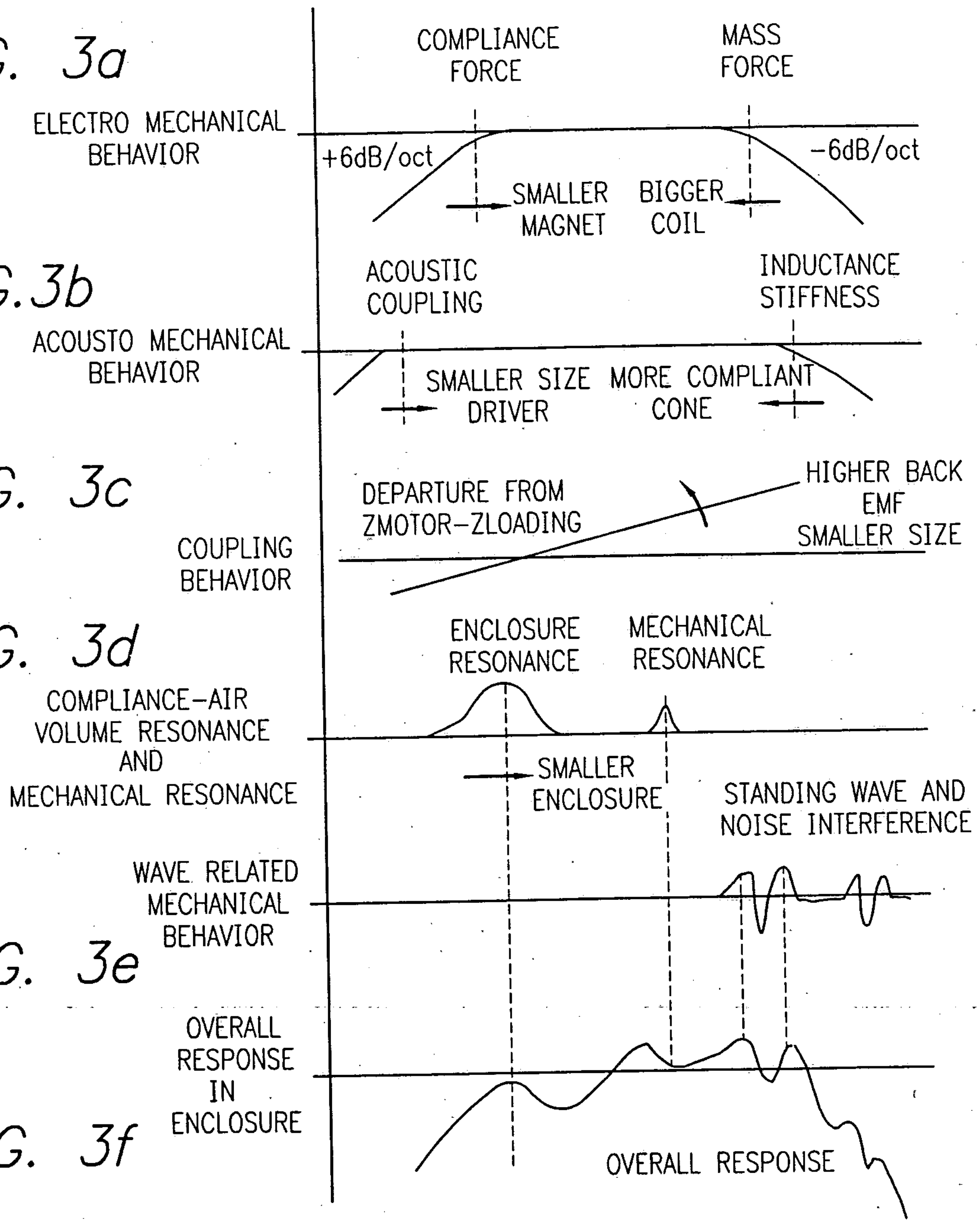
FIG. 3b

FIG. 3c

FIG. 3d

FIG. 3e

FIG. 3f



OVERALL RESPONSE IN ENCLOSURE

FIG. 4a

LOW-HIGH BOOST CROSSOVERS AND SHELF LIMITS

FIG. 4b

LOW-HIGH CUTOFFS AND PEAK COMPENSATION

FIG. 4c

TILT EQ

FIG. 4d

RESONANT NOTCHES

FIG. 4e

HIDDEN NOTCH

FIG. 4f

OVERALL CONJUGATE CORRECTION